

Supernova Neutrino Detection

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World-wide, several detectors currently running or nearing completion are sensitive to a core collapse supernova neutrino signal in the Galaxy. I will briefly describe the nature of the neutrino signal and then survey current and future detection techniques. I will also explore what physics and astrophysics we can learn from the next Galactic core collapse.

1. THE NEUTRINO SIGNAL

Astronomers expect that every 30 years or so, a massive star in our Galaxy will reach the end of its life. When the core of such a star collapses, it emits nearly all of the gravitational binding energy of a neutron star in the form of neutrinos, some $E_b \sim 3 \times 10^{53}$ ergs. Less than 1% of this energy is released in the form of kinetic energy and optically visible radiation. The remainder is radiated in neutrinos, of which approximately 1% is ν_e from an initial “breakout” burst and the remaining 99% are $\nu\bar{\nu}$ pairs from the later cooling reactions, roughly equally distributed among flavors. Average neutrino energies will be about 12 MeV for ν_e , 15 MeV for $\bar{\nu}_e$, and 18 MeV for all other flavors. This hierarchy of energies is explained by the fact $\bar{\nu}_e$ ’s have fewer charged current (CC) interactions with the neutron-rich stellar core than do ν_e ’s; they decouple deeper inside the core where it is hotter and so emerge with higher average energies than do ν_e ’s. Similarly, $\nu_{\mu,\tau}$ ¹, which have only neutral current (NC) interactions with the core’s matter, emerge with even higher energies. The neutrinos are emitted over a total timescale of tens of seconds, with about half emitted during the first 1-2 seconds, and with the spectrum eventually softening as the proto-neutron star cools. Burrows [1] sketches the expected neutrino signal. Some more recent developments in core collapse theory are described in these proceedings by Mezzacappa [2]

¹I will use the symbol $\nu_{\mu,\tau}$ to refer to muon and/or tau neutrinos and their antineutrinos.

and Prakash [3].

2. DETECTORS

Several kinds of detector are capable of detecting a burst of neutrinos from a gravitational collapse in our Galaxy. Most of the detector types described here actually have primary purposes other than supernova neutrino detection, *e.g.* proton decay searches, solar and atmospheric neutrino physics, neutrino oscillation studies, and astrophysical neutrino source searches.

2.1. Scintillation Detectors

The hydrogen in hydrocarbon scintillator has a high cross-section for the charged current (CC) antineutrino absorption reaction,

$$\bar{\nu}_e + p \rightarrow e^+ + n. \quad (1)$$

The positron energy is highly correlated with the neutrino energy. The neutron from reaction 1 may also be detectable via the time-delayed fusion of the neutron with protons in the scintillator:

$$n + p \rightarrow d + \gamma \text{ (2.2 MeV)}, \quad (2)$$

where the γ can be detected by its Compton scattering. The average moderation time for the neutron is $\sim 10 \mu\text{s}$, and the average capture time is $170 \mu\text{s}$; the neutron typically wanders for tens of centimeters before being captured. Therefore, a time-delayed coincidence of a ~ 10 MeV pulse with a ~ 2 MeV signal can provide a signature for the interaction of supernova $\bar{\nu}_e$ in liquid scintillator detectors.

Scintillators are also sensitive to CC and NC neutrino-electron scattering and the superallowed NC excitation of ^{12}C by neutrinos of all flavors, although cross-sections are much lower than for inverse beta decay. The NC ^{12}C excitation can be detected (and, to some extent, be tagged) via the 15 MeV de-excitation gamma; such events should represent about 10% of the total number of interactions, although detection efficiency varies, depending on detector geometry.

Scintillator detectors are not generally able to point to a supernova source. The positron products of the predominant inverse beta decay reaction are emitted nearly isotropically, and the scintillation light is isotropized. However the neutron emission is asymmetric and if the relative positions of the positron and the neutron absorption can be measured, some directional information can be extracted. The CHOOZ experiment [4] has recently demonstrated of this principle using reactor neutrinos.

Currently, the MACRO [5] and LVD [6] detectors at Gran Sasso have enough scintillator mass to be sensitive to a gravitational collapse anywhere in the Galaxy. LSD and Baksan, with less mass and sensitivity, are also still running. Scintillation detectors which will come online over the next several years include Borexino at the Gran Sasso and KamLAND in Japan.

2.2. Water Cherenkov Detectors

The charged current inverse beta decay reaction, reaction 1, will dominate the supernova neutrino interaction rate in water Cherenkov detectors. Therefore, as for scintillator detectors, the primary sensitivity is to the $\bar{\nu}_e$ component of supernova neutrino radiation. Light water Cherenkov detectors are also capable of detecting CC and NC neutrino-electron scattering reactions:

$$\nu_x + e^- \rightarrow \nu_x + e^-, \quad (3)$$

where ν_x represents a neutrino of any flavor. Although elastic scattering events should represent only a few percent of the total supernova signal, this reaction has potential for allowing reconstruction of the direction to the supernova source, because the e^- direction, which can be

determined from the Cherenkov cone direction, is related to the ν_e direction.

Some NC interactions of neutrinos on oxygen are expected,

$$^{16}\text{O} + \nu_x \rightarrow ^{16}\text{O}^* + \nu_x, \quad (4)$$

which can be detected via a cascade of 5-10 MeV de-excitation gammas; these may be useful for neutrino mass measurements (see section 3). Finally, a few percent of interactions will be CC interactions of ν_e and $\bar{\nu}_e$ on ^{16}O and ^{18}O .

The largest existing water Cherenkov detector is the Super-Kamiokande detector [7] in Japan, which should observe thousands of neutrinos from a Galactic supernova.

2.3. Heavy Water Detectors

Heavy water neutrino detectors exploit the relatively high cross-sections for the interaction of neutrinos with deuterons. Both CC and NC deuteron breakup reactions are detectable, via Cherenkov light of the lepton products for the CC case, and via neutron detection of some sort for the NC and $\bar{\nu}_e$ CC cases. Two classes of reactions are relevant here:

1. The neutral current interaction of neutrinos with deuterons:

$$\nu_x + d \rightarrow n + p + \nu_x. \quad (5)$$

In this case the neutron is detected in some way, via Cherenkov light from Compton-scattered gamma rays produced from absorption of the neutrons on nuclei in the detector medium, or using dedicated neutron detectors. The proton is below Cherenkov threshold and is therefore invisible. No energy or neutrino direction is available for this reaction; however, the reaction is sensitive to all flavors of neutrinos.

2. The charged current interaction of electron neutrinos and anti-neutrinos with deuterons:

$$\nu_e + d \rightarrow p + p + e^- \quad (6)$$

$$\bar{\nu}_e + d \rightarrow n + n + e^+. \quad (7)$$

In these cases, the e^+ or e^- can be detected by its Cherenkov light, and energy and directional information can be extracted. In addition, the neutrons from the anti-neutrino reaction can be detected with a time-delayed coincidence (also tagging the anti-neutrino reaction). The products of these reactions retain some information about the direction of the incoming neutrino.

The neutral current (NC) sensitivity of heavy water will make its supernova signal especially rich. In addition to providing a unique diagnostic of supernova processes, a NC detector may be able to provide strong constraints (or measurement) of absolute neutrino mass from relative time of flight measurements (see section 3) in conjunction with CC data from the same detector, or with data from other detectors with primarily $\bar{\nu}_e$ flavor sensitivity.

At present, the only example of a heavy water supernova neutrino detector is the SNO [8] detector in Canada.

2.4. Long String Water Cherenkov Detectors

Long string water Cherenkov detectors consist of long strings of photomultiplier tubes (PMTs) hanging in very clear water or buried in ice. These detector arrays are designed primarily to observe high energy ($>>\text{GeV}$) neutrinos by looking for Cherenkov light from upward-going neutrino-induced muons. However, these detectors have some supernova neutrino sensitivity as well. Although the PMTs in the array are too sparse to allow event-by-event supernova neutrino reconstruction at low energy, a large burst of supernova neutrinos will produce enough Cherenkov photons from interactions in the ice surrounding the PMTs to cause a coincident increase in single PMT count rates from many PMTs [9]. For instance, the track length for 20 MeV positrons in ice is expected to be about 10 cm, from which roughly 3000 Cherenkov photons are emitted [10]; an absorption length of ~ 100 m then leads to an effective volume of $\sim 400 \text{ m}^3$ per PMT. The supernova sensitivity of such a long string detector is strongly dependent on the noisiness of its pho-

totubes and ambient light background. Again, since reaction 1 dominates, primary sensitivity is to $\bar{\nu}_e$. There is no direction sensitivity, although in principle participation in a triangulation measurement using timing is possible.

Examples of long string Cherenkov detectors are AMANDA in the Antarctic ice, the Lake Baikal detector, and NESTOR and ANTARES in the Mediterranean. Currently the most promising for supernova detection in terms of a low background noise rate is the AMANDA detector [10].

2.5. High Z/Neutron Detectors

High Z/neutron detectors are primarily sensitive to the high energy component of the supernova neutrino flux. The idea is to observe neutrons emitted from the NC reaction

$$\nu_x + (A, Z) \rightarrow (A-1, Z) + n + \nu_x. \quad (8)$$

In addition, neutrons can arise from CC neutrino interactions

$$\nu_e + (A, Z) \rightarrow (A-1, Z+1) + n + e^-, \quad (9)$$

$$\bar{\nu}_e + (A, Z) \rightarrow (A-1, Z-1) + n + e^+; \quad (10)$$

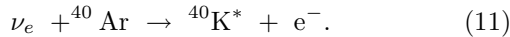
The e^+ or e^- may be detectable as well. These reactions occur primarily for high energy neutrinos; therefore the neutrino flavors detected are expected to be mostly muon and tau (which are emitted with higher temperatures). Just as for the other detectors with NC sensitivity, multi-flavor sensitivity is useful for probing core collapse physics, and will be especially valuable for neutrino mass studies via time delay measurements [11]. High Z materials such as lead or iron are appropriate, since the cross-section increases along with number of nucleons in the nucleus, and a large quantity of relatively pure material can be obtained cheaply. A combination of different materials can give rough neutrino spectral information due to different energy dependence of cross-sections for different nuclei; this in turn can yield information about neutrino oscillation, which would produce distortion of the energy spectra. A particularly promising target material for oscillation tests is ^{208}Pb [12].

Proposed detectors of this type include OMNIS and LAND.

2.6. Other Detectors

Some other supernova-sensitive detectors (existing, under construction, or proposed) are:

- ICANOE (Imaging and CAlorimetric Neutrino Oscillation Experiment): liquid argon drift chambers are to be built at the Gran Sasso Laboratory. These should have sensitivity to ν_e from supernovae via



The final state electron is detected, and in addition the de-excitation gamma rays from ${}^{40}\text{K}^*$ can be detected.

- Radiochemical detectors: the ${}^{37}\text{Cl}$ solar neutrino detector at the Homestake mine, the gallium solar neutrino detectors such as GALLEX and SAGE, or a possible ${}^{127}\text{I}$ detector, will register counts if supernova neutrinos interact inside them. Since the sensitive chemicals are only extracted at very long time intervals (\sim weeks or months), these detectors have no time (or energy) resolution and are of limited value for a stellar collapse search. However, if a burst of gravitational collapse neutrinos were confirmed in one or many of the real-time neutrino detectors, radiochemical experiments could perform prompt extractions to determine whether any counts over background were registered during the relevant time period. Furthermore, recent proposals for quasi-real-time triggered chlorine extractions ([13]) may make radiochemical technology more interesting for supernova neutrinos.
- Gravitational wave detectors: large interferometer experiments under construction such as LIGO and VIRGO will have the capability of detecting gravitational wave signals from asymmetric supernova explosions (although the details of a stellar collapse gravitational wave signal are not yet well understood). The gravitational wave signal may be more prompt even than the neutrino signal.

2.7. Detector Summary

Table 1 gives a brief overview of the neutrino detector types mentioned here.

In summary, scintillator and water Cherenkov detectors are sensitive primarily to $\bar{\nu}_e$; detectors with NC capabilities (heavy water, high Z/neutron) are sensitive to all flavors. Water Cherenkov and heavy water detectors have significant pointing capabilities. All can see neutrinos in real-time, except radiochemical. All have good energy resolution, except long string water Cherenkov, high Z and radiochemical.

Table 2 lists specific supernova neutrino detectors and their capabilities.

3. WHAT CAN WE LEARN?

3.1. Overview

A comprehensive review of all that might be learned from a Galactic signal would be a daunting task, so I will give only a brief overview, and then will focus on the one subject of absolute neutrino mass sensitivity via time of flight.

3.1.1. Neutrino Physics

A core collapse event provides a powerful and distant natural source of neutrinos, allowing the study of neutrino properties, such as mass, flavor oscillations, and charge. Some of the most interesting possible measurements are of absolute neutrino mass, exploiting the time of flight delays over the long distance from the supernova: one can look for an energy-dependent time spread in the observed events, or a flavor-dependent delay. In addition, the effects of neutrino oscillation in the core of the star manifest themselves as an anomalously hot ν_e (or $\bar{\nu}_e$) spectrum (e.g. [12,15]). More information can be extracted: the neutrino data from SN1987A set limits on neutrino lifetime, charge, number of neutrino families, neutrino magnetic moment [14], and even extra dimensions [16]. Although there will always be at least some collapse model dependence in any conclusions, in many cases it is possible to make quite robust assumptions about the neutrino source.

Table 1
Supernova neutrino detector types and their capabilities.

Detector type	Material	Energy	Time	Point	Flavor
scintillator	C,H	y	y	n	$\bar{\nu}_e$
water Cherenkov	H ₂ O	y	y	y	$\bar{\nu}_e$
heavy water	D ₂ O	NC: n CC: y	y y	n y	all $\nu_e, \bar{\nu}_e$
long string water Cherenkov	H ₂ O	n	y	n	$\bar{\nu}_e$
liquid argon	Ar	y	y	y	ν_e
high Z/neutron	NaCl, Pb, Fe	n	y	n	all
radiochemical	³⁷ Cl, ¹²⁷ I, ⁷¹ Ga	n	n	n	ν_e

Table 2
Specific supernova neutrino detectors.

Detector	Type	Mass (kton)	Location	# of events @8.5 kpc	Status
Super-K	H ₂ O Ch.	32	Japan	5000	running
MACRO	scint.	0.6	Italy	150	running
SNO	H ₂ O, D ₂ O	1.4 1	Canada	300 450	running
LVD	scint.	0.7	Italy	170	running
AMANDA	long string	M _{eff} ~0.4/pmt	Antarctica		running
Baksan	scint.	0.33	Russia	50	running
Borexino	scint.	0.3	Italy	100	2001
KamLAND	scint.	1	Japan	300	2001
OMNIS	high Z (Pb/Fe)	10(Fe)+4(Pb)	USA	2000	proposed
LAND	high Z (Pb)		Canada		proposed
Icanoe	liquid argon	9	Italy		2005

3.1.2. Core Collapse Physics

The time structure, energy spectrum and flavor composition of the neutrino burst will yield information on astrophysical stellar collapse processes, even for “silent” collapses, i.e. those occurring without strong electromagnetic fireworks or in regions of the Galaxy obscured by dust. The neutrino signal will help to understand the explosion mechanism and the mechanisms of proto neutron star cooling (see [2,3]). In addition, the formation of a black hole may be signaled by a sharp cutoff in neutrino luminosity [1].

3.1.3. Astronomy from an Early Alert

The neutrino burst produced by the core collapse emerges promptly from the stellar envelope. However, the shock wave produced by the collapse takes some time to travel outwards. The

time of first shock breakout is highly dependent on the nature of the stellar envelope, and can range from minutes for bare-core stars to hours for red giants. For SN1987A, first light was observed about 2.5 hours after the neutrino burst; the first observable photons probably reached us about one hour earlier than that. The observation of very early light from a supernova just after shock breakout is astrophysically very interesting [17], and rare for extragalactic supernovae. One can learn about the supernova progenitor and its immediate environment. And of course, an observation of very early supernova light could also yield entirely unexpected effects. It is possible that a core collapse event will not yield an optically bright supernova, either because the explosion “fizzles”, or because the supernova is in an optically obscured region of the sky. In the lat-

ter case there may still be an observable event in some wavelengths, or in gravitational radiation.

3.2. Absolute Neutrino Mass

The time delay for a neutrino of energy E and mass m_ν is given by $\Delta t = 0.0515 \left(\frac{m_\nu}{E}\right)^2 D$ for a supernova at distance D (for m_ν in eV, E in MeV and D in kpc). Therefore, a spread in arrival time and correlation of arrival time with energy can point to a non-zero neutrino mass, assuming that the neutrinos are emitted with some energy spectrum on a short timescale. However, because there is a relatively large intrinsic emission time spread (~ 10 seconds), one can in practice only get an upper limit on m_ν . For 1987A, for reasonable assumptions about the nature of the source time spread, a typical limit is $m_{\bar{\nu}_e} < 20$ eV. For a supernova in our Galaxy and current detectors, time of flight sensitivity to neutrino mass is around 3 eV for $\bar{\nu}_e$ [18]; this is not better than the best laboratory kinematic limits on m_{ν_e} [19,20].

However, the next supernova may well give us mass limits for ν_μ and ν_τ which are orders of magnitude better than laboratory limits (currently 190 keV for ν_μ and 15.5 MeV for ν_τ [21]). The idea is to use detectors with NC sensitivity to measure relative delays between tagged NC events (which have substantial $\nu_{\mu,\tau}$ component) and $\bar{\nu}_e$, under the assumption that the latter are light enough to have negligible delay and can therefore provide $t = 0$. Information from more than one detector could be used. As an example, the analysis of Beacom and Vogel [22,23] (see Figure 1) shows that Super-K and SNO have sensitivity to $\nu_{\mu,\tau}$ masses in the tens of eV to keV range. Some more recent work [24] shows that a supernova that continues its collapse to a black hole could be even more interesting: in this case, the sharp (\sim sub-millisecond) cutoff in neutrino luminosity, which should be nearly simultaneous for all flavors, provides a clean $t = 0$ for a time of flight delay measurement. If we are lucky enough to observe such a supernova, the energy and time structure of the $\bar{\nu}_e$ cutoff signal could yield $\bar{\nu}_e$ mass limits rivaling laboratory ones. In addition, for proposed detectors such as OMNIS, the relative NC and $\bar{\nu}_e$ time delay could give sensitivity to absolute $\nu_{\mu,\tau}$ masses as low as 6 eV.

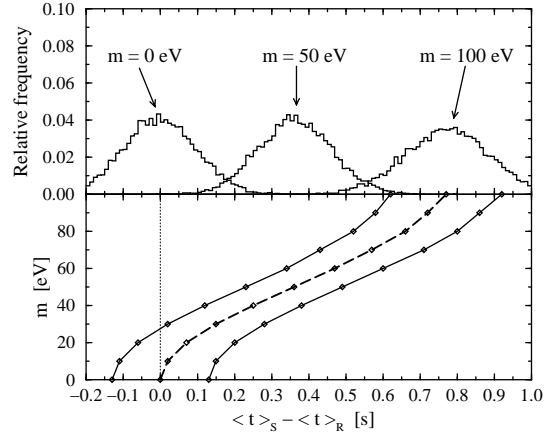


Figure 1. This figure, from reference [22], shows the results of a study of 10000 simulated 10 kpc neutrino bursts in Super-K and SNO. The top frame shows distributions of relative average time delays between NC events tagged in SNO and $\bar{\nu}_e$ events tagged in Super-K, for three representative $\nu_{\mu,\tau}$ masses. The bottom frame shows the 90% C.L. band on neutrino mass that one would obtain for a given measured delay. The vertical line at zero delay shows that one would obtain a 30 eV mass limit for $\nu_{\mu,\tau}$ if the NC events arrive in-time with the $\bar{\nu}_e$'s.

4. SNEWS

As mentioned above, a burst of supernova neutrinos will precede the optical signal by hours or even days; therefore, an early warning to astronomers which could allow unprecedented early light observation may be possible. SNEWS (SuperNova Early Warning System) is an international collaboration of supernova neutrino detectors, with the goal of providing the astronomical community with a very high confidence early alert from the coincidence of neutrino signals in several detectors [25,26]. In addition, the SNEWS alarm may be able to serve as a trigger for detectors which are not able to trigger on a supernova signal by themselves, allowing extra data to be

saved. Currently, MACRO, LVD and Super-K participate; SNO and AMANDA will be the next active members.

Although any early warning is helpful, we would also like to be able to tell astronomers where to look. The question of pointing to the supernova using the neutrino data has been examined in detail in reference [27]. There are two ways of pointing with neutrinos: first, individual detectors can make use of asymmetric reactions for which the products “remember” the direction of the incoming neutrino. Second, the timing of the neutrino signals in several detectors can be used to triangulate; however triangulation will be difficult with the event statistics of current detectors. The best bet will be to use elastic scattering interactions (equation 3) in Super-K. Estimated resolution is several degrees for a 10 kpc supernova.

5. SUMMARY

In summary, several supernova neutrino detectors (Super-K, SNO, MACRO, LVD and AMANDA) with sensitivity to a Galactic supernova are now running. Others (Borexino, KamLAND, possibly OMNIS) will join them shortly. If a stellar core collapse occurs in our Galaxy, in addition to providing an early supernova alert for astronomers, these detectors will record signals from which a wealth of physical and astrophysical information can be mined.

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